Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

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Developing and testing an experimental methodology to study bicycle behavior and operation metrics

TBA4940 - Highway Engineering, Master's Thesis

Master's thesis in Civil and Environmental Engineering
Supervisor: Kelly Pitera
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Preface

This master thesis is written as part of the M.Sc. degree in Civil- and Environmental Engineering at NTNU. The thesis has been written in cooperation with the Department of Civil- and Environmental Engineering at NTNU and COWI, an engineering consulting firm. The experiment has been funded primarily by the Department, although the processing of the video files was funded by COWI.

I would like to thank my supervisors Kelly Pitera and Petr Pokorny for giving me a lot of helpful advice and constructive criticism. I would also like to thank Arvid Aakre for his advice, especially regarding filming of the experiment, and for volunteering his drone and himself as drone operator. Additionally, I would like to thank Preben Lyngaas Jensen and Sara Horseide Fjellvær at COWI who wanted to collaborate, and for both helping and allowing me to utilize their partner-business Data From Sky at their cost.

I want to thank my parents and my sister for always supporting me, giving helpful advice, proofreading the thesis and always making sure that I have no other worries than the task at hand. Finally I would like to thank my friends and classmates for keeping my spirits high during long days and Kristin for her encouragement and support.

Summary

In 2012, the Government introduced a goal of "taking all growth in personal transportation in cites by walking, bicycling and public transport". This has later been famously known as *Nullvekstmålet* or textitthe No Growth Goal. However, the share of trips done with bicycles in Norway has remained relatively stable in Norway since 1985. To increase the share of trips with bicycles, the infrastructure must be designed in such a way that bicycling is perceived as both safer and more efficient than the alternatives. In order to do that, more knowledge about the effects of the design of the infrastructure is needed.

The main objective of this thesis is to develop and assess methodology for executing an outdoor laboratory experiment within the field of bicycle research. The research questions have been articulated in the following way:

> To what degree is an outdoor laboratory experiment a viable way of obtaining data, both operational metrics and behavior, on bicyclists?
>
> How does one plan an outdoor laboratory experiment to study the behavior of bicyclists and what measures must be taken into consideration?
>
> How does one communicate with the participants without influencing them in a successful outdoor laboratory experiment?

To find inspiration for what to study in the experiment, it was decided to observe and film bicyclists at a signalized intersection. After discussing the observation and reviewing the film, it was decided to study how the physical layout of the bicycle roadway at an intersection affects the behavior of bicyclists. Additionally, it was decided to study if a change in behavior in turn will affect the time required for bicyclists to cross the intersection. This would form the basis for the experiment in itself, and allow the author to achieve his main goal in assessing the viability of the chosen methodology to study the behavior of bicyclists.

The layout of the test track was designed to simulate a normal bicycle roadway. Different combinations of geometrical parameters of the infrastructure were tested in an experiment with participants. The participants were recruited through a Facebook-group and the professional and educational network of the author. The experiment was filmed with a drone from above, equipped with a high-quality camera. The video was then processed using Machine Vision by Data From Sky. The video was then analyzed, both using the trajectories created by Data From Sky and visually. Parts of the data from Data From Sky was subjected to a statistical analysis.

The statistical analysis of data obtained through Data From Sky, showed for most scenarios a strong, inverse correlation between the width of the bicycle roadway at an intersection and the time required to cross said intersection. The

data also showed that the length of the width extension had no impact on the time required to cross the cross-section at the end of the active area.

Based on the visual analysis of the approach, there is evidence that as the width increases, bicyclists tend to utilize the width to a larger degree. Additionally, the participants do seem to take bicyclists travelling in the opposite direction into account when approaching the intersection. However, when length of the width extensions was not long enough, it led to conflict between the opposing movements. The visual analysis of the merging proved to be difficult and the methodology proved to be inadequate, and it is therefore recommended in the future to study this using a different methodology.

After the results and method was discussed, some weaknesses and limitations in the method were discussed. These weaknesses and limitations were identified to be: communication to the participants, realism of the design of the experiment, sample size and demography, test size, the time of year, the inter-personal behavior and resource usage.

Finally, the viability of the chosen methodology's ability to obtain operation metrics and studying bicyclist behavior was assessed. It was concluded that the methodology would be viable as long as the researchers know the weaknesses, limits and strengths, and could therefore be applied to experiments in the future.

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1 Introduction

The world is constantly changing, old challenges are solved and new challenges appear. After humans built the first cities and started the process of urbanization, too many people in the same place has led to difficulties. In the transportation sector, the horse posed a threat over a 100 years ago [1]. The author states that it was estimated in 1894, that by 1950 every street in London would be covered by 9 feet of horse manure. Horses also occupied more space than trucks today, and if injured in the road they would simply be shot and/or left there creating an obstruction. During the two first decades of the 20th century, automobiles gradually replaced the horse and it was viewed as a major environmental solution at the time. 100 years later, it is now widely regarded as a bad move.

There are multiple reasons for why automobiles are now viewed in the same light as horses at the end of the 19th century. In 2014, it was reported that ownership of cars in Norway was 572 cars per 1 000 inhabitants. Car traffic has increased steadily to the point where the infrastructure cannot supply the necessary service level during rush hours. In Oslo in 2016, drivers spent on average 145 hours extra in traffic congestion [2]. During the afternoon rush, their travel time increased by 69 %. According to the same article, in Bergen, drivers spent on average 74 hours extra in traffic congestion for the same year. This not only affects themselves, but other road users as well. Recently, a Norwegian newspaper, abc nyheter, reported that during rush hours each bus is on average delayed by 6-7 minutes [3].

Private car usage, according to Statistics Norway, a Norwegian government statistics bureau, were responsible for 65 % of the 10 million tons of CO_2-equivalents related to road traffic in 2015 [4]. Statistics Norway also reports that the total amount of greenhouse gas emissions in 2015 was approximately 54 million tons CO_2-equivalents, which means that private car usage was responsible for 12 % of all greenhouse emissions [5]. Fridstrøm, a researcher at ITE, states that the real emissions NO_X-gases, which are dangerous, are shown to deviate by up to 2000 % from laboratory tests [6]. He further states that noise, another important externality from car traffic will not improve in the future. Although electric cars do not have a combustion engine, the noise component from combustion engines are relatively small compared to the noise component from the wheels, especially at higher speeds.

The Parliament of Norway introduced a legislation in 2018 called Klimaloven, or the Climate Change Act in English [7][8]. The law states a target for reduction in greenhouse gas emissions to be reduced by at least 40 % compared to the reference year 1990. This equals a reduction of at least 55 % compared to 2015. According to Fridstrøm, these reductions must primarily happen in sectors not subjected to quotas, which includes agriculture, fishing, construction and transportation. [6] The reason for this is that the target goal is only set for sectors not subjected to quotas, and for the remaining sectors Norway can simply buy quotas to meet the independent target goal [9]. The same target for reduction in greenhouse gas emissions was first set to be achieved by 2020 in Klimaforliket 2012 [10], an agreement on climate politics between every political party except for The Progress Party [11]. However, now that the target is legislated, it should be considered to be more substantiated. In Klimaforliket 2012, the Government introduced a goal of "taking all growth in personal transportation in cites by walking, bicycling and public transport". This has later been famously known as Nullvekstmålet or No Growth Goal, due to not wanting any more growth in personal car usage.

These two acts from the Government illustrates political will to act on the matter of both greenhouse gas emissions from and congestion due to cars. The battle for livable cities (and global warming) is on, as illustrated by the local government being pressured into removing rush hour pricing in Rogaland due to populistic demands [12]. This is a step in the wrong direction, and to help people and politicians make the right changes, gaining more knowledge within the field of bicycles might be a step in the right direction.

The share of trips done with bicycles in Norway has remained relatively stable in Norway since 1985 according to the Travel Behavior Survey 2013/2014 [13]. The Norwegian Institute of Transportation Economics has since 1985 surveyed a sample of the Norwegian population on their travel behavior and produced a report with their findings every few years. However, this responsibility was recently transferred to the Ministry of Transport and managed by the Norwegian Public Roads Administration from 2016 [14]. The NPRA has not yet completed the report, but some preliminary findings have been published [15]. Their findings so far report little change in the share of trips made with bicycles.

Therefore, it is hard to draw any conclusions on a national level, but assuming that the share of trips with bicycles are approximately constant seems to be true. To increase the share of trips with bicycles, the infrastructure must be designed in such a way that bicycling is perceived as both safer and more efficient. In order to do that, more knowledge about the effects of the design of the infrastructure is needed.

This thesis attempts to contribute to the knowledge around bicycle infrastructure design, and does so using a unique methodology: an experiment with participants set up in a controlled environment. This method will henceforth be identified as an outdoor laboratory experiment.

1.1 State of the art literature review

The literature search started with the author being handed a paper written by researchers from TU Delft [16], and realizing he wanted to do something similar. From the paper, two more relevant articles discussed in it, were discovered [17],[18]. In addition, the search engines of Google Scholar, Google, Oria and ITE (toi.no) has been utilized to search for relevant articles, papers and other sources to complete the literature review. The keywords used in the searches were combinations of: bicycle, intersection, traffic signal, signalized stop, traffic flow, capacity, design.

For this thesis, the most important aspect has been the methodology on how to carry out a laboratory experiment for researching bicycle behavior. There are limited papers available that employs a laboratory experiment methodology in the field of bicycle research, at least that has been discovered by the author. Therefore, whilst the general design of such an experiment can be drawn from these papers, all the specifications, execution plans and details had to be developed by the author. For this reason, the literature found cannot be used for comparisons in most cases.

At TU Delft, the researchers carried out an experiment to study how directly opposing bicyclists avoid collision [16]. The article details how the experiment had participants bicycle in controlled conditions on a test area with two cameras that recorded the experiment. The video was then processed, analyzed and trajectories were found, combined (due to having two cameras) and then studied.

Researchers in Santiago studied the saturation flows of bicyclists at a signalized stop [17]. To do this, the researchers found a designated location, a 2,0 m wide two-way bicycle roadway with a traffic signal. 20 participants were recruited and asked to bicycle through the signaled portion of the roadway again and again. The experiment was performed with widths from 1,0 m to 2,0 m, and only in one direction. They found a slightly exponential relationship between the saturation flow and the width of the lane, ranging from approximately 2000 bicycle/h·lane for 1,0 m width to 4500 bicycle/h·lane for 2,0 m width.

Andresen et al. developed a Necessary-Deceleration-Model, a car-following model for bicyclists and employed a controlled laboratory experiment with participants to calibrate and validate their model [18]. Their methodology is a bit similar to the researchers at TU Delft in that the experiment was filmed with two cameras. The trajectories was then exported and used to study fundamental traffic parameters: headway, desired speed (Free-flow speed), flow and density. However, the article does not describe their method in detail.

The laboratory experiment designed by the author attempts to recreate a bicycle path with a signalized stop/intersection. Therefore, literature regarding bicycle operations through a signalizes stop/an intersection were searched for. Highway

Capacity Manual (HCM) 2016 Chapter 4 states that capacity is rarely observed on bicycle facilities, and argues therefore that the values found for uninterrupted flow are based upon what is essentially incomplete data [19]. It is further stated that the capacity is only relevant at signalized intersections, according to Danish Guidelines [20]. In the Norwegian Handbook for Geometric design of roads and streets, there is no mention of bicycle flow through an intersection [21].

For on-street facilities, HCM2016 Chapter 19 discusses the capacity and saturation flow of a bicycle lane through an intersection [22]. The difference between the saturation flow and capacity can quickly be described in that the saturation flow is a theoretical flow not accounting for green time or other factors whereas the capacity is the actual flow you would observe [23]. HCM further states that based on an assumption that the saturation flow of a bicycle lane equals 2000 bicycles/h, and a known cycle length and effective green time for the bicycle movement for the relevant intersection, the capacity can be calculated. Note here that a lane width of 5,0 ft (approximately 1,5 m) is suggested as a default value. This value is therefore lower than what the researchers in Santiagio found in their laboratory experiment [17].

$$c_b = s_b \cdot \frac{g_b}{C} \tag{1}$$

where
c_b = capacity of the bicycle lane [bicycles/h]
s_b = saturation flow of the bicycle lane = 2000 [bicycles/h]
g_b = effective green time for the bicycle lane [s]
C = cycle length [s]

For off-street facilities, there is no methodology or discussion regarding bicycling through an intersection as this would be regarded an on-street facility by default. However, there is a discussion on the relationship between the path width and the number of effective lanes for an exclusive bicycle path.

Path Width [ft]	**Path Width [m]**	**Effective Lanes**
8.0-10.5	2.4-3.2	2
11.0-14.5	3.4-4.4	3
15.0-20.0	4.6-6.1	4

Table 1: Exhibit 24-14 in HCM2016, Chapter 24 [24]. The path width listed in metric values is not part of the original table, but added by the author if this thesis.

The national guidelines show a tendency to not detail the bicycle flow parameters through an intersection, and instead relies on suggested values if anything. A few researchers has performed laboratory experiments to study bicycle operations, and the author of this thesis intends to study this area through a similar method.

1.2 Research questions

The main objective of this thesis is to develop and assess methodology for executing a laboratory experiment within the field of bicycle research. The main research question has been articulated in the following way:

> To what degree is a laboratory experiment a viable way of obtaining operation metrics and studying bicyclist behavior?

Operation metrics can here be interpreted as the metrics related to the operational service of the infrastructure. These metrics are in this case the standard traffic flow parameters such as speed, density and especially flow in the experiment. Additionally, two secondary research questions are formulated:

> How does one plan an outdoor laboratory experiment to study the behavior of bicyclists and what measures must be taken into consideration?
>
> How does one communicate with the participants without influencing them in a successful outdoor laboratory experiment?

Within the primary objective of the thesis, there had to be developed an experiment with its own research objectives. These are introduced in section 2.4, and their purpose is to help assess the methodology through establishing clear goals for the experiment itself.

2 Methodology

In this section, the methodology behind the experiment is presented. As the methodology is experimental and developed by the author, the methodology has been structured chronologically and parts of the process are detailed to help create some context. The methodology details how the experiment came about, how it was designed and planned. Then the plan for filming the experiment and analysing the data is presented. Finally, the research objectives for the experiment is presented.

2.1 Designing an experiment

The master thesis is a continuation of the work from the project thesis that was written in the spring of 2019. Therefore, the general idea to perform an outdoor laboratory experiment was decided, but exactly what to study in the experiment was uncertain. The conclusion from the project thesis was that the required minimum widths of bicycle roadways in Norway was not decided on the basis of research, but rather empirical observation and status quo in other countries [25].

2.1.1 The initial thought process and development of the study objective

During early discussions, it was agreed that it would be difficult to execute an outdoor laboratory experiment with the goal of achieving full capacity of a bicycle roadway. Additionally, several sources in the literature review of the project thesis indicated that the only situations where one would ordinarily achieve capacity issues on a bicycle roadway is at signalized stops/intersections [19] [20].

Therefore, it was decided to observe and film bicyclists at a signalized intersection to observe the behavior and gain inspiration for an experimental study. This was done with the Miovision Scout, a camera owned by the Department, during the morning rush at the intersection next to Sluppen Bridge. The location of the bridge in Trondheim is shown in Figure 0 and an aerial view of the area is shown in Figure 0. This location was well suited for the observation because of the number of bicyclists using the infrastructure. Although, it is a combined pedestrian- and bicycle roadway, there are limited numbers of pedestrians using the same roadway.

Figure 1: Left: Aerial view of Trondheim with the location of Sluppen Bridge (Sluppen Bridge) marked with a red square. Right: Aerial view of Sluppen Bridge area, the relevant intersection is to the west of the bridge.

On the day of the observation, the 16th of September, from 07:15 - 07:45, there was moderate to heavy rain. Still, there was a substantial amount of bicyclists travelling presumably to work. Some general observations that were noted were an even share of both men and women bicycling, and also an even share of traditional bicycles and electric bicycles. Neither of these observations have been quantified. The most interesting observation however, was the way bicyclists lined up when waiting for the green light. Figure 2 shows how bicyclists lined up during one red light, and illustrates the average observed behavior.

Figure 2: Screenshot from the video recorded at Sluppen Bridge during the observation.

Typically, from the observations, most of the bicyclists lined up in a line while a few bicyclists maneuvered towards the front of the queue, standing next to other bicyclists, presumably to be able to cross the intersection and pass other bicyclists quicker. From observation, the green time for the bicyclists was about 16 seconds and those were shared with a right movement of vehicles. This conflict is illustrated in Figure 3.

Figure 3: Illustration of the route of the bicyclists and the right movement of cars that share the same green time.

The right movement of the cars is not protected, and therefore they have to yield for the bicyclists. During the afternoon rush, although the bicyclists primarily bicycle in the opposite direction, this leads to a queue building up over the bridge for the cars. At one point it was observed that from the light turned green and the bicyclists started bicycling to the last bicyclists started to cross the intersection, about 15 seconds which equals almost the whole green time, passed. This led to considerations about the way bicyclists line up before an intersection, the physical design of the intersection, and the (green) time required for bicyclists to cross the intersection.

A noteworthy detail about the physical layout at Sluppen bridge is that the combined pedestrian- and bicycle roadway is parallel to the road so that bicyclists have to make a sharp 90 degree turn. After the bicyclists have crossed the intersection most would have to cross the Sluppen bridge which has a combined pedestrian- and bicycle roadway of approximately only 2,0 m as seen in Figure 3. Therefore, a reason for why bicyclists tend to line up in a row could be that they are familiar with their route and know that for the next 100-200 m they will have to bicycle in a line. The bicyclists that maneuver towards the front could perhaps be doing this of the same reason; to try to beat the other bicyclists to the confined part of the infrastructure so as to not be stuck behind bicyclists bicycling at speeds lower than his/her own desired speed.

After discussing the observation and reviewing the film, it was decided that the effect of the physical layout of the bicycle roadway before and after an intersection has on the behavior of bicyclists could be studied, and if that in turn will affect the time required for bicyclists to cross the intersection. This would form the basis for the experiment in itself, and allow the author to achieve his main goal in assessing the viability of the chosen methodology to obtain operation metrics and study the behavior of bicyclists.

It was decided to generalize the intersection situation, and thus it was agreed to study a situation where the participants would bicycle straight forward through an intersection. It is hypothesized that the behavior observed at the Sluppen bridge was in part due to the small width at the intersection and that will be studied. The hypothesis can be expressed as follows:

> As the width of the intersection increases, the participants are able to utilize the width and in turn this will increase the traffic flow of all bicyclists waiting at the traffic light to cross the intersection. Additionally, the length of the width extension will also help reduce the time required to cross the intersection by allowing the participants to merge over an increased length.

2.1.2 Designing the physical layout of the test track

The physical layout of the track comprises of several key components; the length of the test track, the width and width extensions, the lengths of the width extension. These elements will be explained further below. In addition there are many more components of the experiment to consider such as how to physically mark up the track in a way that is intuitive for the participants to understand and quick to change the layout between runs.

Width and width extensions

The width and width extensions were perhaps the most important component due to their role in the hypothesis. The initial proposal was to employ width extensions that would yield widths equal to the different minimum widths found in N100. However, through discussions and the pilot testing it was decided to target widths similar to N100, but slightly different; 2,5 m, 3,5 m and 5,0 m. The reason for this is that the difference between the widths in N100 would perhaps be to small to yield any results. It was also decided that the base width of the test track before and after the width extension should be 2,5m. The layout for the Scenario with a width of 2,5 m, Scenario 1, is illustrated in Figure 4 as well as the positions of the participants and the team members. Considering that the base width is 2,5 m, the width extensions are effectively 0 m, 1,0 m and 2,5 m.

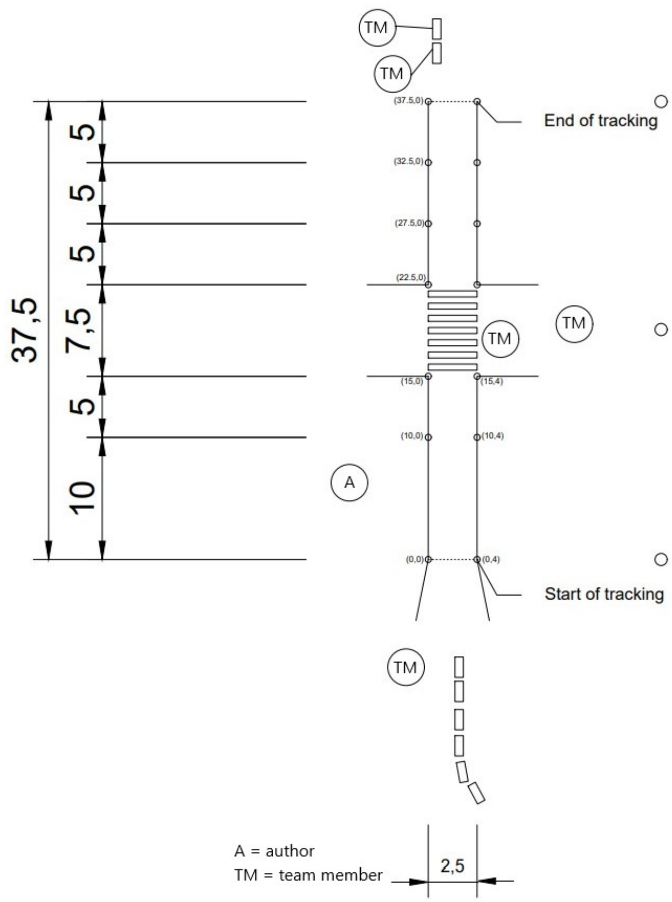


Figure 4: Drawing made in AutoCAD for Scenario 1 and with an overview of participants and team members.

In Scenario 1, there is no width extension before and after the intersection. In Figure 5 however, there is a width expansion of 2,5 m which means a total width of 5,0 m at the start and at the end of the intersection. In order to avoid any confusion, for the rest of the report only the total width at the start and the end of the intersection will be discussed, and there will not be any values mentioned in regards to just the width extension itself.

Length of width extensions

A lesser part of the hypothesis is the length of the width extensions. The merging part was however more uncertain due to the fact that there was no video of the merging from the observation at Sluppen bridge and the observers were too focused on the approach. During the observation, the camera simply could not capture both bicyclists lining up and how they merged back during and/or after the intersection. Therefore, it was decided to study if the length affects the merging behavior and what length was required for bicyclists to merge comfortably. The length of the width extension has two functions; to allow bicyclists to diverge and utilize the width before an intersection, and to allow bicyclists to merge back together after the intersection.

Knowing what lengths to employ was a challenge to figure out due to several reasons. Firstly, due to the length of the width extension having two functions, it would make sense to have different lengths before and after the intersection. However, in a real world scenario it is likely that an intersection would be designed as symmetric as possible for simplicity's sake. Therefore it was decided to find lengths that could work as both a staging area and a merging area. Secondly, due to little information gathered on merging behavior during the observation at Sluppen Bridge, engineering judgement were employed to decide on sensible lengths. These lengths were decided after discussion to be 5,0 m and 10,0 m. Scenario 5, which has a width of 5,0 m and a length of the width extension of 10,0 m, is illustrated in Figure 5.

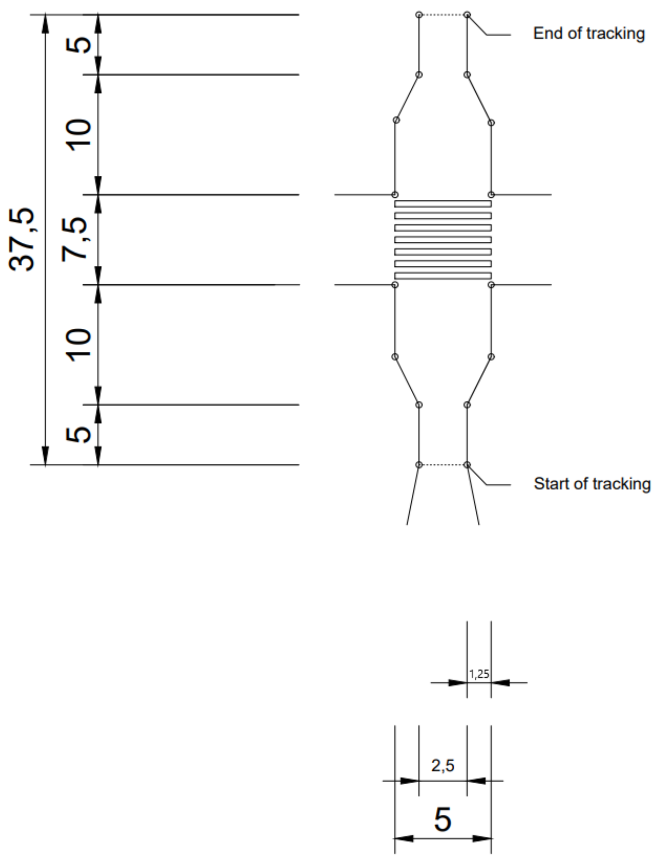


Figure 5: Drawing made in AutoCAD for Scenario 5.

In order to avoid confusion, for most the report, the length of the width extensions will be talked about simply as the length. And when there are other lengths that are discussed, they will be identified as such.

General layout
The layout of the test track was required to recreate/simulate a normal bicycle roadway. A major discussion point was whether to set it up as one half of the whole roadway with participants travelling in only one direction or to set it up as the whole roadway with participants travelling in two directions. The main argument for the first proposal was that it requires fewer resources and would therefore be easier to execute. The main argument for the latter is that it will likely be more realistic and this will allow participants to be able to use more than their half of the roadway if they should desire to do so. In the end, it was

decided to go with the second option.

Test track length, active area, tracked area and test area

The majority of the track length is decided by the length of the intersection crossing and the length of the width extensions. The width of the crossing road, which counts as part of the length of our test track was decided to be 7,5 m which is common for Norwegian roads. For the scenarios with 10,0 m of length extension, this would mean a minimum of 27,5 m was required. Although it was expected that it would be inside these 27,5 m, the active area, the significant behavior would take place, it would still be prudent to make the test track longer. Therefore, another 5,0 m was added to each end making the total track length 37,5 m. The tracked area would therefore be the test track length by the variable width. The test area includes the staging area outside the start of the test track, the test track, and the outside of 3 cones to force the bicyclists out of the cameras view. In other words, what the camera could film plus some more. Figure 6 illustrates the different area types defined by the author.

Figure 6: Illustration of the different area types defined by the author.

Marking the layout of the test track

To mark up the test track, there were mainly two options that were considered, either using cones or chalk. Cones are visible, easy to move and is a physical marking. However, it would be harder to organize them in a straight line and they're not a continuous marking. Chalk on the other hand is a continuous marking, but it can also be hard to draw straight lines and it would require there to be multiple straight lines on the ground or multiple test areas. Therefore, using cones was our choice. The Department had cones available, and we were also able to borrow a van to transport the cones and other equipment to the experiment site.

2.2 Planning the execution of the experiment

The planning of the execution of the experiment consisted of 5 parts that are described in detail in the following sub-subsections.

2.2.1 General plan

The experiment would test combinations of 3 different widths and two different lengths, however one scenario does not have a width extension, yielding a total of 5 different scenarios. The scenarios are shown in Table 2 with their respective test orders and specifications.

Scenario	Test order	Runs	Width [m]	Length [m]
1	2 (and 6)	6	2,5	N/A
2	4	3	3,5	5,0
3	1	3	3,5	10,0
4	3	3	5,0	5,0
5	5	3	5,0	10,0

Table 2: Table of the different scenarios, their test order and specifications.

In every scenario, the participants would start outside the test track in a set order and bicycle into it. The intersection they would have to cross is signalized, and the light is red when the participants arrive. A team member functions as the light, with a flag, and waving the flag means that the light turns green. The participants then continue bicycling through the test track and when exiting the test track, bicycles around on the outside of 3 cones to remove them from the cameras view.

It was not planned to perform Scenario 1 twice, but decided to this during the experiment. Therefore, in Table 2 it is listed as two tests with 3 runs each to have a complete overview. The remaining four scenarios was repeated three times. The scenarios are repeated several times to give each scenario some statistical weight. There is some learning from the participants to be expected, so after a while the repeating of a scenario might not be that important. However, the main limiting factor for the numbers of runs per scenario, was the battery capacity of the drone and number of batteries.

2.2.2 Recruitment of participants

The initial plan was to recruit participants through a Facebook-group for bicycle-interested people in Trondheim. A survey asking participants for demographical information and contact information was posted in the group. However, few people actually signed up as participants. Therefore, recruitment was done at the offices of COWI in Trondheim and through friends, classmates and other students. There were no definite goals for the demography of the group, but from our observations, a fairly even ratio of males to females as well as traditional bicycles to electric bicycles was desired.

2.2.3 Information given to participants

It was concluded through discussion that the participants should behave naturally and of their own free will (with an aim of bicycling the route as set by the author). If the participants know what the hypothesis is, they might act in that way and thus creating a self-fulfilling prophecy. If the participants know too little information, they might overthink the experiment and perhaps try to guess the correct behavior instead of behaving as they naturally would.

It was therefore decided that the information given to the participants would roughly be the following:
1. In regards to the purpose of the experiment, participants were told that we were studying the behavior of bicyclists through a signalized intersection. This is true, but it is also a very vague description.
2. Bicyclists were given a number between 1-11, and were told to always line up in the staging area and enter the test track in that order, but that inside the test track they did not need to follow the order. They were also told to bicycle inside the test track how they wanted, and to go at the speed they would normally bicycle at if they were for example travelling to the university or the office.
3. A walkthrough of the test track and -area was given, so that the bicyclists knew where to bicycle but not how. They were also told how the signalized intersection worked.

2.2.4 Instructions to the team members

For the execution of the experiment to run smooth, two more employees (Research Assistants) at NTNU were engaged in addition to the supervisors/advisors. In total, 6 people including the author were responsible in conducting the experiment. Two of the team members were instructed to bicycle in the opposite direction of the participants, one would start when the participants started and the other would start when the light turned green. One team member was instructed to function as the green light, by signaling a green light about 10-20 seconds after the first participant had stopped, at her own discretion. One team member was assigned to starting off the participants from the staging area, after a visual sign from the final team member who was responsible for filming the experiment. The author himself was overseeing the whole operation, making small adjustments, observing and taking notes.

2.2.5 Filming of experiment

The filming of the experiment was done to acquire video that could then be analyzed in order to either prove or disprove the hypothesis. In addition, filming the experiment allows the author (and others) to study the experiment multiple times and to test multiple software programs if needed. The active area, the intersection and the 10,0 m immediately before and after the intersection, is where the participants was primarily studied. Therefore, the most important part of the filming is that the active area is always in view. Of course, being able to view more than just the active area as well is nice.

For the observation at Sluppen Bridge, the Miovision Scout was used. The Scout [26], designed for filming traffic consists of a low quality, super wide-angle lens on top of an 8,0 m telescope pole connected to a battery and control interface that allows the camera to record for a long time. It can also be programmed to film certain time intervals, for example the morning- and afternoon rush hour traffic. Full specifications can be found in the appendix. The one drawback of the Scout, was that the camera could not capture the full extent of the planned test track.

Therefore, when considering the filming, it was decided to draw inspiration from new methods that are recently employed in the field. At COWI, a method of gathering traffic counts for different movements in an intersection is to utilize a drone fitted with a high quality camera to record the traffic. Arvid, an employee with the Department, owned a DJI Phantom 4 Pro. The Phantom 4 Pro[27], is a professional-level drone with a high quality, wide angle camera attached. The drone can fly up to 6000 m above sea level, and the battery lasts up to 30 minutes.

By employing the Phantom 4 Pro as our camera of choice, the author was able to film the experiment from above. This resulted in a top-down which was a very favorable view for studying the film later. It also captured the length of the test track without issue.

2.3 Analysis of the video

The analysis of the video consisted of 3 steps that are described in detail in the following parts.

2.3.1 Preparation of the video file for tracking

The experiment was filmed in multiple segments, capturing one scenario per video file, to avoid using battery whilst the test track was changed in between the scenarios. Therefore, all the video files were edited together into one video file with a title screen in between them to help identify the test number and thus the scenario number corresponding to the information in Table 2. In addition, unnecessary delays were removed from the video to reduce the length of the video and the size of the file.

2.3.2 Processing and tracking of the video - machine vision

Data From Sky (DFS)[1], a technology owned by RCE Systems, was used to track the bicyclists in the video. In a COWI manual, RCE Systems describe their process as utilizing Deep Neural Networking more commonly known as Deep Learning and Machine Vision, a typical application of Deep Neural Networks. This process is complex and due to it's own design, a black box. In simple terms; the tracking is done directly on the video file by an Artificial Intelligence and quality controlled by humans. This alleviates the need for manual, time-consuming work that would be required for other software programs such as T-analyst, an open source software program developed at Lund University. In T-analyst, the video file is split into frames that a human then has to manually track for every x-th frame.

2.3.3 Data- and video analysis in Data From Sky

In DFS, there are different types of gates that interacts with the trajectories and are directionally dependent. There are neutral gates that will count the number of bicyclists (or other traffic modes) passing through them and DFS will give the speeds and accelerations for that instant moment in time. The other type of gates are exit- and entry gates that have to be used in combination. DFS will in this case calculate average speeds for the correlating combinations. As this software has been developed for traffic counting amongst other things uses, the same bicyclist cannot be counted through multiple entry- or exit gates.

Figure 7 shows what the author sees after the video and tracking log is fully edited and data is ready to be exported. The position of gates are shown, although it's mostly gate 3 - Intersection_End and 4 - Track_End that is used.

[1]https://datafromsky.com/

Figure 7: Screenshot from DFS showing placement of gates and trajectories for one run.

The final steps of the analysis can be explained as follows:

1. Place gates across the width of the test track on the video. The gates interact with the trajectories, and timestamps at different positions can be obtained.

2. The raw data is then exported to Excel where the data is subjected to statistical analysis. Based on the timestamps and a known amount of participants, the data is categorized into the different runs and scenarios. The time stamps are converted from milliseconds to seconds with only 1 decimal (based on the assumption that there are larger inaccuracies than a tenth of a second), and the irrelevant columns are omitted. Finally, time intervals are calculated from the different time stamps.

3. The data is then manipulated in the desired way and visualized. Averages as well as standard deviations are calculated. T-tests are performed on the different data sets, as well as a calculation of Hedges' g.

2.4 Research objectives of the experiment

Based upon the research questions in the Introduction and the hypothesis earlier in this section, there are several specific research objectives that will be looked into. The research objectives and the experiment is primarily a vehicle to allow the author to achieve his main goal in answering the research questions that concern the development of the methodology.

The research objectives for the analysis has been defined as:

1. Will an increased width of the bicycle roadway at an intersection reduce the time-to-cross, which is expected to increase the traffic flow through an intersection?

2. How does bicyclists approach the intersection and how much of the space do they occupy?

3. Will an increased length allow bicyclists to merge smoother and thus increase their speed through the intersection?

4. Will the length of the width extension affect the point where the merging starts or ends?

3 Results and discussion

This section is made up of four parts; first results and discussion from the analysis is presented, including a discussion of the research objectives. Next, the results and discussion of the methodology (in light of the results of the experiment) are presented, followed by the weaknesses and limitations of the method. Finally, a discussion of the viability of the methodology where the research questions are discussed.

3.1 Results and discussion from the analysis

A total of five scenarios were tested, numbered 1 to 5. The scenarios are sorted by the following rules: 1) from smallest width to largest and 2) from shortest length of the width extension to the longest. Table 3 gives a quick overview over the designs of each scenario.

Scenario	Width [m]	Length [m]
1	2,5	N/A
2	3,5	5,0
3	3,5	10,0
4	5,0	5,0
5	5,0	10,0

Table 3: A summary of the scenarios and their specifications.

The results found were either based on the trajectories generated by DFS and by using the DFS software subject to statistical analysis to Excel, or through visual analysis.

3.1.1 Time-to-cross an intersection

The data in this section are obtained using Data From Sky subject to statistical analysis in Excel. The data was processed to find out the effects of the bicycle-infrastructure geometrical parameters on the traffic flow of bicyclists through a signalized intersection. The analysis of this data answered two research objectives. The first research objective was:

> Will an increased width of the bicycle roadway at an intersection reduce the time-to-cross, which is expected to increase the traffic flow through an intersection? (Research objective 1 from section 2.4)

To answer the research objective, the time-to-cross has to be defined and identified. When using time-to-cross, the author implies the time interval from the light turns green to the bicyclist crosses past the end of the intersection. This means that the time interval does not correspond to a set distance, as the participants may be positioned at any point in front of the intersection. In every run, the time-to-cross was further specified for two cases, one average time-to-cross of all bicyclists and a time-to-cross for only the last bicyclist. These times were then averaged for each scenario.

Figure 8 shows the average time-to-cross of all bicyclists and the time-to-cross for the last bicyclist. The numbers below are all averaged from the three runs for each scenario, except for Scenario 1 which was repeated 6 times.

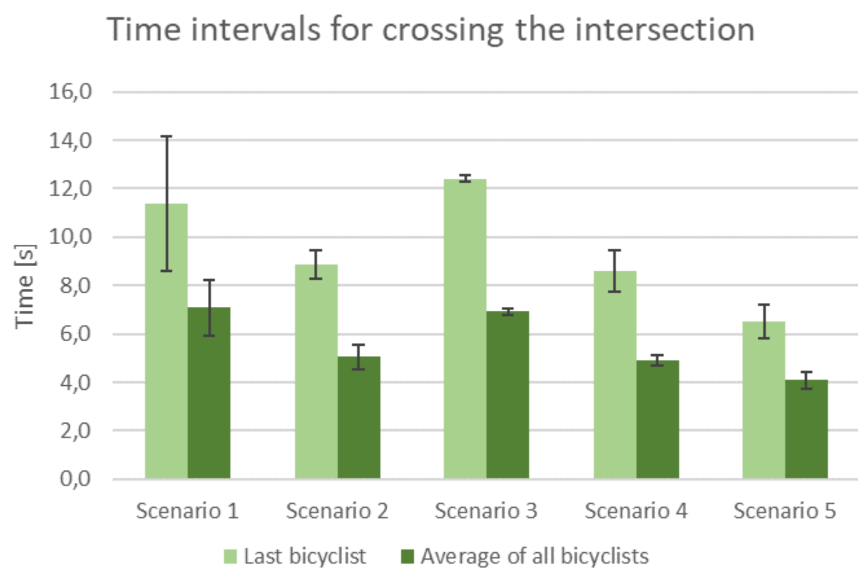


Figure 8: Graph over the time interval for crossing the intersection (= time-to-cross) for all participants and the last bicyclist for each scenario.

Both time intervals in Figure 8 show a similar trend, although it should be noted that the average time-to-cross of partially dependent on the time-to-cross for the last bicyclist. However, the figures show that the average bicyclist and the last bicyclist is affected similarly by the changes in infrastructure. Note that a high number means that the time-to-cross is high and the speed is low. In this instance, a lower number is better.

A standout result is that Scenario 3 showed a slower time through the intersection compared to Scenario 2, although the only difference was that the length extension was 10,0 m contrary to 5,0 m. This can be explained by the passive bicycling and the early green light signals given in the first runs, as detailed more closely later in section 3.2.

To see if there was a significant difference in the means of the different scenarios and runs, several t-tests were done on the different data sets. The alpha-level for all tests was set to 5 %.

Data set 1	Data set 2	t-value	p-value	Result
Scenario 1 Runs 1-3	Scenario 1 Runs 4-6	-0.38863	.698187	Not significant
Scenario 2	Scenario 3	1.84774	.066913	Not significant
Scenario 1 Runs 1-6	Scenario 5	3.27352	.001256	Significant

Table 4: Overview of the t-tests that were done for which scenarios.

Although they yielded similar results, a t-test was performed on Scenario 1 runs 1-3 as one set and Scenario 1 runs 4-6 as the other set. The first three runs were performed very early in the experiment and the last three runs were performed towards the end of the experiment. Because there was not a significant difference in their means, it can be argued that the results are constant within the scenarios. Therefore, it can be assumed that the behavior within the experiment time-frame was constant.

As stated above, the results yielded by Scenario 3 are slower than one would have expected. However, to see if the difference is statistically significant, a t-test was performed on Scenario 2 and 3. The result of the test showed that the difference was not statistically significant.

Finally, a t-test was performed on Scenario 1 and 5 to see if the change in the geometrical parameters of the infrastructure has any statistically significant effect on the results. The test proved that this was the case.To measure the effect size, Hedges' g was calculated.

$$\text{Hedges' g} = \frac{M_1 - M_2}{SD^*_{pooled}} = \frac{(4.26 - 5.61)}{7.648694} = 0.176501.$$

Where M1 - M2 equals the difference in means and SD$^*_{pooled}$ equals the pooled and weighted standard deviation. A value of 0.17 means that the effect size is small statistically. It also means that the difference in means is equivalent to 0.17 standard deviations. However, this must be seen in connection to the area of study.

If the results from Scenario 3 is considered invalid, there is evidence of a high correlation between the width of a bicycle roadway at an intersection and the time-to-cross the intersection. It is expected that a reduced time-to-cross would increase the traffic flow through the intersection as a reduced time-to-cross implies a higher speed, and flow is a product of density and speed. This is also in line with Exhibit 24-14 in HCM2016, that states a correlation between the path width and the amount of effective lanes. If the number of effective lanes increase, then it is likely that the traffic flow would increase as well. Therefore, the answer to research objective 1 would be that yes, the time-to-cross through an intersection is reduced with an increased width of the bicycle roadway at the intersection and it is expected that this will increase the traffic flow through the intersection.

The second research objective was: The time to the end of the active area were also measured in an attempt to answer research objective 4:

> Will an increased length allow bicyclists to merge smoother and thus increase their speed through the intersection? (Research question 3 from section 2.4)

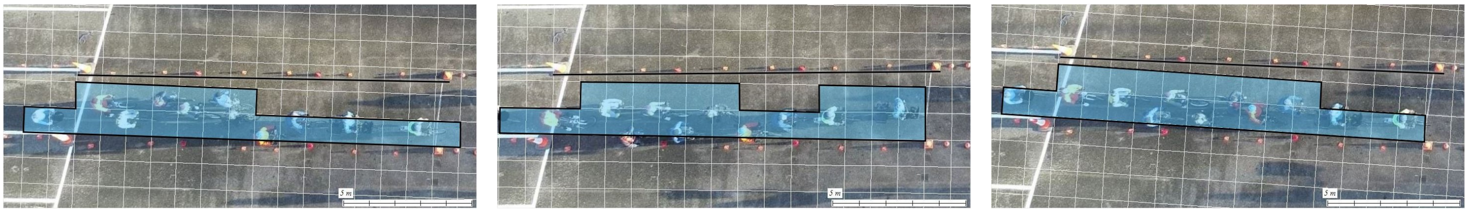
The time-to-cross found for the end of the active area however, showed results equal to those of the end of the intersection + 2,6 seconds with a standard deviation of 0,1. This is evidence that the length had little to no impact on the traffic flow through and immediately after an intersection.

3.1.2 Approaches

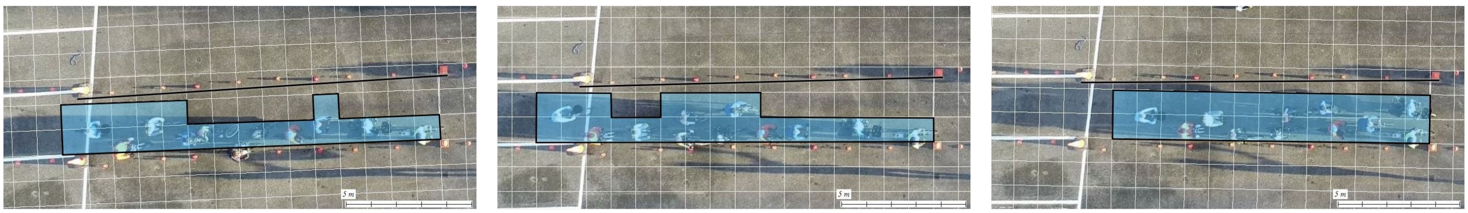
The second analysis method is visual and relies on still photos from the video. Because the experiment was filmed from above in high quality the behavior of the participants can easily be studied at a later time. Additionally, a grid pattern has been overlaid the photos and the occupied grids are highlighted to quantify the space used. Each square is approximately 1x1 m. Squares that are not occupied might still be considered as occupied if they are located in between participants and there is not enough space to maneuver into them. This process is a bit subjective in nature. Through this method, research objective 4 can be answered:

> How does bicyclists approach the intersection and how much of the space do they occupy? (Research question 2 from section 2.4)

Shown in Figures 9 through 13 is the position of all participants as the light turns green for the five different scenarios. The grid pattern and the occupied space highlighted in light blue is visible.



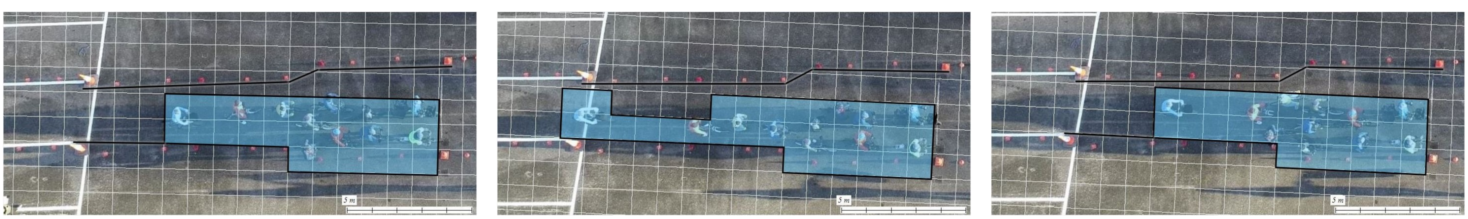
(1) Run 1 (2) Run 2 (3) Run 3



(4) Run 5 (5) Run 5 (6) Run 6

Figure 9: Approaches for Scenario 1.

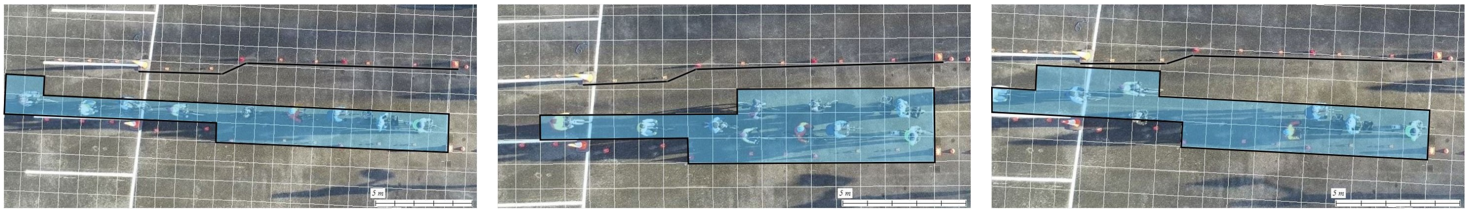
The participants seemed to mostly line up in a row, but in some scenarios, some of the participants chose to line up adjacent, perhaps a little staggered to each other. The width utilized is usually not more than approximately 50 %. The queue length is approximately 12-15 m. On average, the participants use 24,3 m^2, resulting in an average density of 2,2 m/participant.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 10: Approaches for Scenario 2.

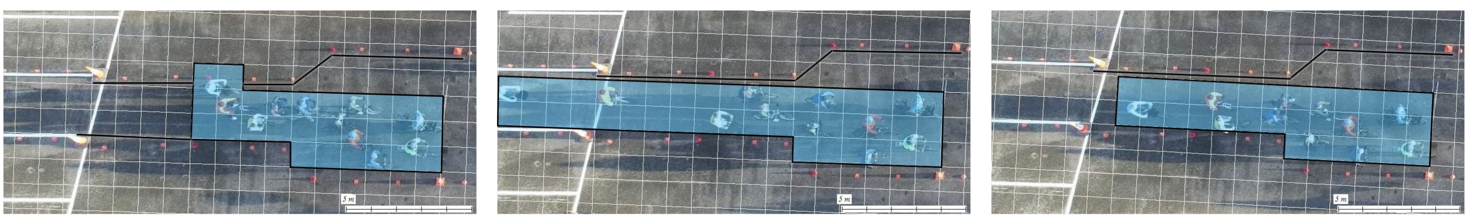
The participants now choose to line up adjacent to others so that they're now mostly 2 bicyclists side by side. In some cases, they're almost 3 bicyclists side by side although a bit staggered. For the most part, the participants are utilizing approximately 50 % of the width, but a tendency to utilize more now is appearing. The queue length is approximately 10 m. On average, the participants use 29,3 m^2, resulting in an average density of 2,7 m/participant.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 11: Approaches for Scenario 3.

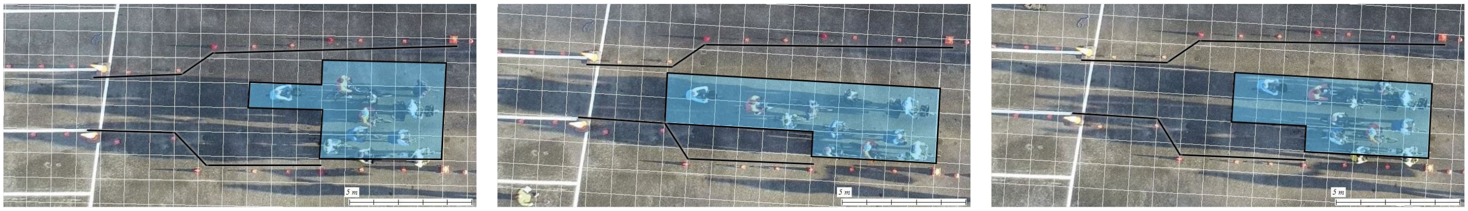
For most of the participants for most of the runs, they chose to line up in a row. However, in some instances there are participants adjacent to another so that there are 2 bicyclists side by side, perhaps a bit staggered. The participants are utilizing the width less than they did in Scenario 2. The queue length is difficult to estimate, but approximately 10-15 m seems to be a reasonable estimate. On average, the participants use 34,6 m^2, resulting in an average density of 3,1 m/participant. Note that these results, as other results from Scenario 3, are likely invalid.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 12: Approaches for Scenario 4.

The participants are utilizing mostly at least 50 % of the width. This actually created some issues with passing for the team members bicycling in the opposite direction. Because the length of the width extension is only 5,0 m, the queue length of the participants build up to this point or even past it which creates a confined section for the team members to pass who instead had to slow down a bit. The participants also seems to leave a little gap where the width extensions starts, this can likely be explained by the sharp angle. The queue length is approximately 10 m. On average, the participants use 34,0 m^2, resulting in an average density of 3,1 m/participant.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 13: Approaches for Scenario 5.

The participants are still utilizing at least 50 % of the width, however they are now packed more dense compared to Scenario 4. There are now 3-4 bicyclists side by side waiting at the intersection. The queue length is now as little as 6-7 m. On average, the participants use 23,6 m^2, resulting in an average density of 2,1 m/participant.

Based on Figures 9 through 13, there is evidence that the participants does line up differently when the infrastructure changes. There are two trends that can be identified. First, as the width increases, bicyclists tend to line up across the width to a larger degree. Although around 50 % of the width is utilized, when the width increases the relative width utilized increases as well. This can perhaps be explained that the participants are taking the team members bicycling in the other direction into account. However, if the length of the width extensions is not long enough it might lead to conflict between the opposing movements.

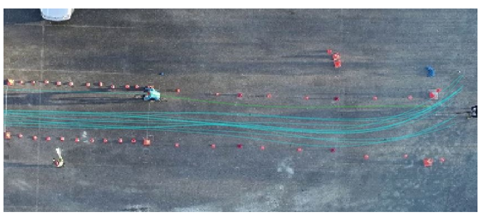
Second, as the length of the width extension increases, it can be argued that the participants utilize the width better and are able to pack much denser. Note that the last bicyclists are often trying to avoid coming to a stop, and since the grid analysis includes all bicyclists, these results give a higher number. This level of density was not observed during the real-life observations, but perhaps the facilities at Sluppen does not provide the level of comfort required for the bicyclists to position themselves this close to each other. The first bicyclist tends to park on the left side of the bicycle lane and other bicyclists would then have to maneuver to utilize the space to the right of the first bicyclist. Due to the preference of positioning oneself close to the middle, there is a tendency to block some space on the right where the width extension start, and or a "tail" of participants to develop along the unmarked centerline. As Scenario 3 did not allow for all the participants to approach the intersection, this is based upon the video from only Scenario 4 and 5. The design of the physical layout does not consider the slope of the width extension, and it is probable that it affects the utilization of the width.

3.1.3 Merging

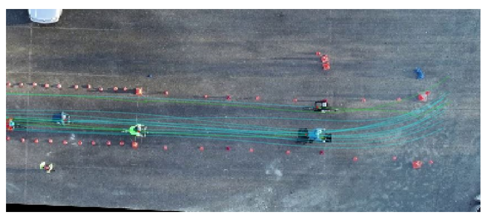
To study the merging, a visual analysis was done. However, the still photos are taken from the DFS software so that the trajectories can be utilized. Therefore, the data set being analysed is based upon both the recorded video and data from DFS. The merging of bicyclists is hard to illustrate using still images from the video due to the merging taking place over both space and time. A trajectory consists of two components, the path and the momentum for every point along the path. The trajectories generated by DFS will overlay the path the bicyclists use, and it was hoped that this would yield insight so that research objective 4 could be answered:

> Will the length of the width extension affect the point where the merging starts or ends? (Research objective 4 in section 2.4)

Figures 14 through 18 are screenshots taken from the DFS software. The blue lines in the pictures are the trajectories for every single participant in that run. Based on the paths, some information can be drawn.



(1) Run 1



(2) Run 2

(3) Run 3

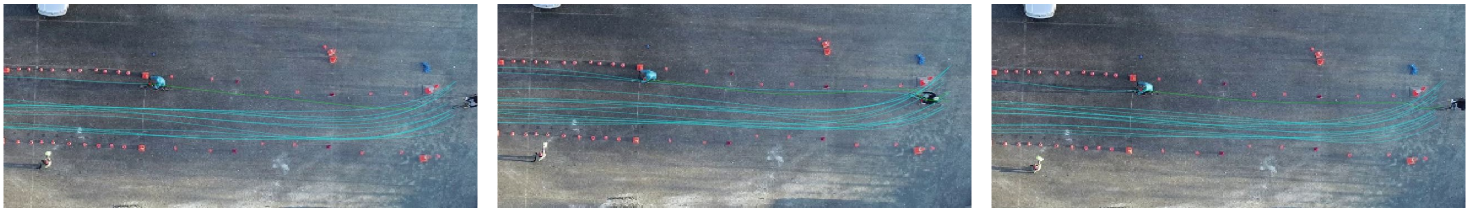
(4) Run 4

(5) Run 5

(6) Run 6

Figure 14: Merging for Scenario 1.

As the participants are generally lined up in a row, there is generally little merging happening. In run 5 and 6 the participants hindered the desired movement of the team members bicycling in the opposite direction.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 15: Merging for Scenario 2.

In this scenario, there was more merging happening, though most either had no need to merge and a few decided not to merge but rather continue bicycling side by side with another participant.

(1) Run 1 (2) Run 2 (3) Run 3

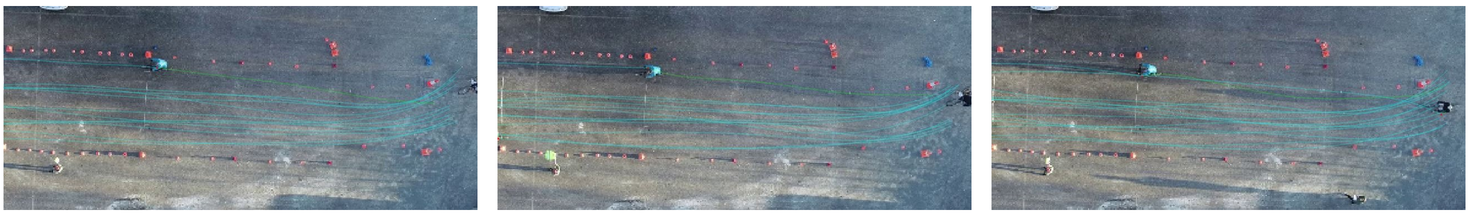
Figure 16: Merging for Scenario 3.

There was almost no merging within this scenario. For the most part, the participants were bicycling in a line or two staggered lines.

(1) Run 1 (2) Run 2 (3) Run 3

Figure 17: Merging for Scenario 4.

During the runs in this scenario, several different types of behavior was observed. In one run, the team members bicycling in the opposite direction were hindered partially due to the participants not showing any desire to merge. In the next run, there was some conflicts during the merging which lead to some participants having to slow down. In the final run, there was some merging but it happened very smooth. Most of the participants however chose to bicycle side by side with another participants, perhaps a little staggered.



(1) Run 1 (2) Run 2 (3) Run 3

Figure 18: Merging for Scenario 5.

For this final scenario, the participants often were lined up 3 bicyclists across the width. During the runs, there was a decent amount of merging, however the participants that merged often merged to bicycle 2 bicyclists across the width through the rest of the track.

Depending on the location of the paths, the level of individually chosen paths can be seen. In Scenario 3, run 1, all the paths are located in the same space. Because multiple people cannot occupy the same space at the same time, it can be assumed from the picture that people in this scenario tended to follow the person in front. From watching the video, the author can confirm this assumption. In Scenario 4, run 3, the paths seem to be located along two different spaces, thus it can be assumed that the participants generally bicycled side by side. The video showed that this was true for half the participants while the remain half was staggered. This proved the need for video analysis to either confirm or dispute these assumptions. A trend that can be argued for is that as the width increases, so does the width utilized by the participants.

From observing the video, the merging behavior of participants were to a large extent non-existing. The participants often bicycled in pairs after reaching the end of the width extension, sometime just a bit staggered. The groups resistance to merging can perhaps be attributed to a belief that either after the second team member had passed on bicycle in the opposite direction or after they had passed the intersection, the experiment was over. Another reason might be that they were not treating the other participants as strangers, and therefore did not mind bicycling side by side. The participants also often took the shortest route out of the intersection, this can perhaps also be attributed to a belief that the experiment was over. Anyhow, the behavior of the participants after the intersection does not seem realistic and the results from this section of the test track are likely invalid. As the results are considered invalid, the research objective is difficult to answer. Perhaps the merging behavior of bicyclists should be studied in an separate experiment with different methodology.

3.2 Results and discussion from the methodology

The results and discussion from the methodology is presented in a similar structure as the methodology.

3.2.1 Preparation

The recruitment of participants proved to be difficult. The author assumed that the Facebook-group *På Sykkel i Trondheim* (*On the bicycle in Trondheim*) would be an ideal place to search for participants, but in total only one person from this group showed up. Instead, the author was forced to recruit from friends, classmates and professional acquaintances. A reason for the few volunteers might be that the experiment was executed in early November with temperatures just above zero degrees Celsius. The majority of the participants turned out to be students, and that may be due to the reward. For an adult with a full time job, getting a free pizza meal for 1-2 hours of volunteering might not be viewed as good enough compensation, however it was hoped that recruiting amongst people who are passionate for bicycling would not require extra outer motivation. However, for a student the same reward might be viewed in a far more positive regard. A lot of the students had in some way a connection to the author, and loyalty/friendship/compassion might play a part in why they showed up. Therefore, in the future, it could be recommended to both schedule the experiment closer to summertime and consider employing a different reward strategy such as for example giving out a 1 000 NOK gift card to one participant.

During the pilot test, the need for a rope became apparent. When setting up the test track, it was hard to create straight lines. Instead, the edge lines of the test track became either concave or convex and it took multiple tries to form relatively straight lines. The widths of the test track had originally been planned to be 4,0 m, 6,0 m and 8,0 m, working from an assumption that we were to test a high-capacity bicycle road and therefore not testing for values below the maximum required minimum width in N100. However, when setting up the track, it was realized that the planned widths were too extreme. One thing that was not discovered during the pilot test was that the uneven pavement allowed for water to form 2-3 thin pools that was frozen for the time of the experiment, leaving the original placement of the test track unusable. The track was therefore moved approximately 5 m to the side, resulting in some small changes in the route to return to the staging area for the participants and the placement and angle of the drones camera.

During the initial setup of the test track for the experiment, the rope was used in addition to the two measurement wheels. This resulted in straight edge lines, however those sides were not parallel so that at the end of the test track the width is likely closer to 3,0 m. In addition to this, the total length of the test track was supposed to be 37,5 m, but in the end the total length showed to only be 37,0 m. There were several attempts to correct the layout of the test track, but with not enough time to completely re-do the track before the participants showed up, the discrepancies were accepted and worked around. The process of making changes to the physical layout could have been improved by having a shorter rope to make it easier to place the cones on a straight line or using a chalk line marker to mark up the lines between the cones.

To produce valid results for the merging of the participants, several measures could have been taken. The two most important ones would have been to extend the length of the test track, and to have either more team members bicycling in the other direction in the test track or delay the second bicyclist so that they will interact with the participants during the merging section. This could likely stop the participants from taking the shortest route out of the test track as well. Another idea would have been to chalked up a centerline to force participants to stay within their half of the roadway.

3.2.2 Communication and info given to participants

The verbal instructions to the participants was written down and remembered in Norwegian. However, as one of the participants preferred English to Norwegian, the author had to translate on the fly. The instructions were likely not completely understood, perhaps due to the translations or the other participants knowledge of English. This is assumed on the basis of the participants behavior at the start of the experiment.

During the test run to learn the route and test the participants understanding of the intersection and traffic light function, the participants forgot to stop for the red light, and that part was once again explained. In the first run, people showed a tendency to just follow the cyclist in front of them in a passive manner. They were therefore told once again that they only had to start in the specified order, but that they did not have to stay in that order inside the track. They were also told that they could use more of the width if they wanted to and it was also specified that this was a two-direction bicycle roadway (as exemplified by the two team members that were cycling in the other direction). This led to questions from the participants such as “Can we overtake?!” to which they were given the answer “yes”. The next run, some of the participants started cycling more aggressively, perhaps too aggressive with overtakings before the intersection. Although this was more desirable than the passive cycling, it proves the challenge of tailoring the communication to achieve the right behavior from participants. The final run of the first test, Scenario 3, showed once again a bit passive bicycling. In the future, it would be recommended to write the instructions in both Norwegian and English, and to have an outsider listen to them and check for ambiguity. Finally, it is recommended to read from a manuscript to ensure all details are given exactly as planned.

3.2.3 Executing the experiment

After a few runs, the lead cyclist asked if he should assume that light was red when they started bicycling and if he could see that it was red, because if so then he would slow down for the light. He was told this assumption is correct. This is another indication that the information to the participants was ambiguous. When observing the experiments and later the video, it is evident that some participants were very eager to get to the front of the queue before the intersection. The motivations of these eager participants are unknown. However, as most of the other participants were more passive and some even trying to slow their speeds to avoid coming to a stop, it is possible that everyone operated on the same assumption that the light is red, and that they were simply for eager to be the first ones to cross the intersection.

Before the experiment started, the research assistant functioning as the traffic signal was told "to give the green light about 15 seconds after the first person arrives at the green light". This was based upon a simple guess by the author that a headway of 1 seconds was reasonable, and that any difference would be absorbed by the stop before the intersection, and with 15 participants planned for this would equal 15 seconds. However, and perhaps due to the passive bicycling at the start, this resulted in the green light being given before too many participants could line up during most of the first runs. This can explain why the time for Scenario 3 is so high as shown in Graph 8. After a few runs, it was agreed upon that the green light was not to be given until most of the participants had approached the intersection.

During the experiment, in between the runs, it was decided to run Scenario 1 once again to see if there had been a change in behavior. The second run of Scenario 1, runs 4-6, showed no change in behavior. The author thought that the behavior from Scenario 3 was not realistic, yet he did not think to prioritize to redo this scenario. One important lesson, even if you have a pilot, is that it could be smart to start off the experiment by running a fake scenario that you are not measuring. This allows one to make the needed changes on the fly and ensure that the first data that you attempt to gather are not affected by unforeseen behavior.

A phenomenon that was observed was that the participants forwent their personal space to a larger degree compared to the individuals observed in real-life. In addition, this phenomenon was observed more frequently with larger widths. At 2,5 m, the participants lined up mostly in a row and perhaps stopped with less space in front of them than observed in real-life. However, when the width was increased to 3,5 m and 5,0 m, they lined up shoulder to shoulder with strangers and even bicycled together out of the test track, something that was not observed at Sluppen. In the future, it would be recommended to keep the participants estranged by for example not having them stand in a line possibly allowing for small talk but rather spread out. Also, some of the participants had connections to each other which might have had an impact on their inter-personal interaction and behavior.

During the experiment, due to the positioning of the track, the time of day and the season, the sun was setting just over the horizon which led to the participants unfortunately having to bicycle directly into the sunlight which probably blinded them or posed some discomfort to an extent. This was not discovered during the testing as that was performed just after sunset, but before it became too dark. This experiment was executed during the first weekend of November, the last possible weekend before the temperature dropped to below 0 degrees Celsius and the roads were coated in a thin layer of frost and ice. Therefore, if the experiment had not been successful, there would not have been enough time to prepare a new one. This is another reason why it would be advisable to plan for bicycle-experiments to happen earlier in the autumn.

In total, the execution of the experiment itself was both faster and easier than expected. The team members executed their responsibilities well, to change the physical layout of the test track took approximately 1 minute, and all participants were compliant. The DJI Phantom 4 Pro was quick to fly into position and was able to film stable and from approximately the same position every time. The battery capacity of the drone was in total assumed to result in around 1 hr of filming (20 minutes per battery), and the amount of runs that we were able to do was estimated based on this. In total, it was assumed that we could perform close to 30 runs. However, after the 19th and final run was done, the 3rd battery was at 40 %. The reason for this discrepancy can be attributed to forgetting to charge the first battery after the pilot, starting the 1st battery at only 70 % and the cold weather which effectively reduces the available battery capacity.

3.2.4 Filming of the experiment

To film the experiment with the DJI Phantom 4 Pro instead of the Miovision Scout was arguably a good choice. In actuality, the Miovision Scout was set up as a backup camera, but the film was in the end not required. However, it helps to visualise the difference in how well the experiment was captured. As can be seen in Figure 19 and 20, the area captured with the DJI Phantom 4 Pro is significantly larger and the camera quality and resolution is significantly improved compared to the Miovision Scout.

Using the drone allowed the experiment to take place over the length and area that it did. If the choice to film with a drone had not been made, either the experiment in its executed from could not have been executed or we would have had to for example set up the Miovision Scout on top of a building.

Figure 19: Screenshot from the video recorded during the experiment with the Miovision Scout.

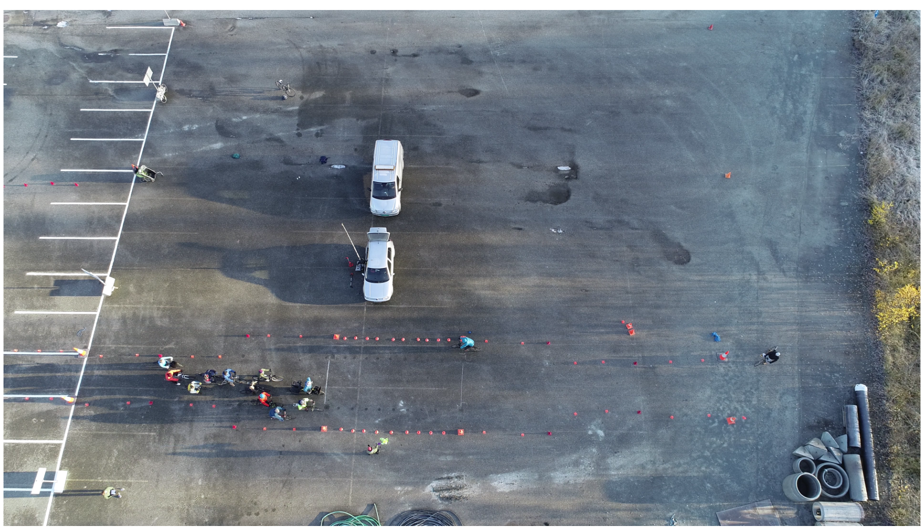


Figure 20: Screenshot from the video recorded during the experiment with the DJI Phantom 4 Pro.

3.2.5 Comparison of results from DFS with T-analyst

As DFS can be compared to a black box (inherently due to its design based upon Neural Networks), T-analyst was used to find the trajectories for some participants as well. T-analyst is an open-source software developed at Lund University in Sweden. The same data has been used in both softwares, and therefore the results found should be similar. To make the comparison, the trajectory for the same participant in the same run was compared for the speed at the same point along the path. This was repeated for three participants, and the results are presented in Table 5

Data From Sky	T-analyst	Difference [km/h]
20,1	20,5	-0,4
20,2	19,6	0,6
15,9	17,1	-1,2
Average		-0,3

Table 5: Comparison of the results from Data From Sky and T-analyst using the same data set as input.

For two of the three participants, their speed was found to be approximately the same. For the third participant, the difference was greater. The average difference was -0,3 seconds and the standard deviation was 0,9. The different results does not necessarily mean that one software is returning wrong results.

In T-analyst, there was no calibration of the camera to correct for any distortion. Essentially, it was assumed that the camera filmed from above and that the camera view was equal to the map. Additionally, the tracking in T-analyst is done manually, and therefore the tracking was done every 15th frame or every 0,5 seconds (the video was recorded at 30 frames per second). The trajectory is calculated based on every frame where the participant is tracked and estimations in between. In DFS however, it is known that there has been done a calibration of the camera to correct for distortion. The method for tracking the bicyclists is unknown, but it is assumed that the tracking is done more frequently. Therefore, the result found through T-analyst is known to be "correct", however with two imperfections. This result is not too different from the one found through DFS, so it can be argued that DFS is likely producing valid results and the difference is created by the imperfections of the method using T-analyst.

3.3 Weaknesses and limitations of the method

Every method has its weaknesses and limitations, including this one. Some were known beforehand, and some were discovered during the planning or the experiment. The weaknesses are mostly regarding sub-optimal execution of the experiment, while the limitations are mostly regarding the assessment of the viability of the chosen methodology. The weaknesses and limitations are presented in no specific order:

1. Communication to participants.
   This has been a weak point in the planning and execution of the experiment as it has lead to some concerns and uncertainties. The instructions to modify the behavior might have influenced the behavior to align more with the authors hypothesis, resulting in skewed results. The validity of these results can therefore be questioned, however the author believes that at worst the participants behavior is only exaggerated a bit.

2. Realism of the designs of the experiment.
   As the experiment had a relatively small budget and was based on changing the infrastructure, cones and chalk were used instead of curbstones and road paint. For budgetary reasons, a person was employed to function as a traffic light.

3. Sample size and demography.
   There were only 11 participants, comprising mostly of male students. However, the experiment was not intended to provide valid results for the Norwegian population.

4. Test size.
   Only a limited number of runs per experiment was done, as the battery capacity of the drone was a limiting factor.

5. Time of year.
   The low temperatures might have affected the level of comfort and the behavior of participants, and the early sunset forced the experiment to be executed at a non-central location which likely lowered the attractiveness of volunteering.

6. Inter-personal behavior.
   As some of the participants shared relations and they were all grouped together thus becoming familiar, they were not as estranged as the bicyclists observed in real-life. This led to forgoing their personal space to a larger degree than in real-life situations.

7. Resource usage.
   This experimental methodology relies on a lot of resources in the form of participants, team members and to a degree; money. If large data sets are desired to provide more reliable results, the scenarios would have to be repeated more times, possibly with multiple sets of participants as well.

3.4 Viability of the methodology

The main purpose of this thesis was to develop and evaluate an experimental methodology for bicycle research involving filming participants bicycling on a test track under controlled conditions. This was illustrated by the primary research question:

> To what degree is a laboratory experiment a viable way of obtaining operation metrics and studying bicyclist behavior?

Additionally, two secondary research questions were formulated:

> How does one plan an outdoor laboratory experiment to study the behavior of bicyclists and what measures must be taken into consideration?
>
> How does one communicate with the participants without influencing them in a successful outdoor laboratory experiment?

The experiment has shown that data, both operation metrics and the behavior of bicyclists can be obtained from this methodology. Through Data From Sky, time stamps were gathered for different cross-sections, and the operational metrics could be gathered and further subjected to a statistical analysis. By using Data From Sky, a lot of manual work and time was saved, which is increasingly positive when the data set size is larger. Utilizing a drone allowed the researcher to capture the behavior from excellent angles and in high quality so that the video could be studied later.

When planning an outdoor laboratory experiment, there are some key measures that is strongly recommended. Having a field observation was very helpful in that we were able to observe one type of behavior, and hypothesize why the bicyclists behaved as they did and how their behavior would change with different layouts of the infrastructure. Having a pilot test was absolutely necessary to identify sub-optimal designs and revise the plans, as well as familiarize the team members with the setup. Additionally, there must be a plan for what to study, what data/type of results are required and how to obtain them from the experiment.

In regards to the communication, the first step should be to agree on the purpose of the communication, as well as what information is necessary. Additionally, it should be judged how the level of information will affect the behavior of the participants/the results from the experiments. When the methodology behind the communication is developed, write down the information to the participants in every relevant language and check with an outsider that the information is easily understood. Next, read from the written down information during the information to control what information has been given. Finally, if any questions are asked during the experiment, think through what you're going to say and write down what was said and when it was said to check for changes in behavior.

As the experiment was executed under controlled conditions, outside factors may not have affected the participants. Therefore, such a method will likely not reproduce results obtained from a real-life scenario. However, this allows the researcher to study the effect of one or few specific factor(s). Sometimes, such as in this case, the desired situation (read: infrastructure) to study may not be readily available and if the experiment relies on changing the infrastructure, then it will be difficult to find matching locations to study. In other cases, where there are similar real-life conditions, the experimental data could be validated with field data.

Furthermore, the evaluation of the experiment methodology highlighted some weaknesses and limitations. The weaknesses could be negated by better planning and insight, and the limitations would have to be accounted for within the scope. As new technology is developed and improved, it is likely that a digital approach to observing behavior will become increasingly more common. Therefore, parts of the methodology could be applied for field observations as well. In total, the methodology would be viable as long as the researchers know the weaknesses, limits and strengths, and could therefore be applied to experiments in the future.

4 Conclusion

The main purpose of this thesis was to develop and evaluate an experimental methodology for bicycle research involving filming participants bicycling on a test track in controlled conditions. The experiment has shown that data, both behavioral and the behavior of bicyclists can be obtained from this methodology. The method also illustrated some strengths, namely the quality of recording and processing trajectories of larger data sets through Data From Sky.

Furthermore, the evaluation of the experiment methodology highlighted some weaknesses and limitations. The weaknesses of the method could be negated by better planning and insight, and the limitations would have to be accounted for within the scope.

4.1 Future work

As has been stated numerous times throughout the thesis, the merging was always an unknown factor and no valid results were found. Therefore, the merging behavior could be studied in detail and through a different or improved methodology. Some of the discussion in section 3.2.2 and 3.2.3 could be relevant in that case.

The methodology involves two technologies; Data From Sky and drones. The strengths of DFS are obtaining operation metrics such as speed and acceleration of a bicyclists without manual work. The strengths of drones are capturing behavior extremely well in high-quality from a favorable angle. Therefore, this methodology could work really well in future experiments where the operation metrics are of interest for large data sets.

The thesis might be of interest to professors employed at and students writing theses for the department if they were to do a similar experiment. This means that the methodology could be developed and tested further to generalize the methodology for various experiments. However, future experiments based upon a similar methodology, especially to the strengths mentioned above, could shift the focus more towards the experiment itself as it is now more mature.

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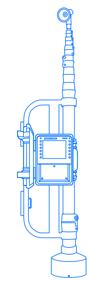
Appendices

A Specifications for the Miovision Scout

Miovision Scout

Scout System Package Contents

- Scout Control Unit (1):
  Lock with Key (2)
  Miovision Ultra SD Card (1)
  USB SD Card Reader (1)
  Universal Charger &
  Regional Power Cord (1)
- Power Pack (Additional 96 hours of recording time) (1)
- Scout Connect
- Scout Pole Mount (1)
- Accessory Case (1)
  Scout Camera (1)
  Ratchet Straps (2)
  TR30 Screw Driver (1)
  Lock with Key (2)



Miovision Scout Hardware

Weight	
Control Unit	24 lb (10.89kg)
Pole Mount	18 lb (8.16kg)
Power Pack	40.4 lb (13.79kg)

Battery and Power	
Built-in Battery	12 V, 28 Ah sealed lead acid battery
Battery Life	72 hours (3 days)
Battery Life (with Power Pack)	72 hours + 96 hours (7 days)
Stand-By	2 months
Recharge Time	5-6 hours (typical)
Temperature impact on battery capacity	104°F (40°C) to 102% rated capacity; 77°F (25°C) to 100% rated capacity; 32°F (0°C) to 85% rated capacity; 5°F (-15°C) to 65% rated capacity.
Battery Lifespan	Up to 60% capacity after 500 full charge and discharge cycles
Power Adapter	50/60 Hz, 100VAC-240VAC; European power cord available.

Scout Display	
Dimensions	4.5" x 3.375" (114.3 mm x 85.7 mm)
Screen Type	Backlit LCD

Video Recording	
Video Format	h264 codec; .mp4 file format
Video File Size	384 kbps (~180 MB/ hour of video)
Resolution	720 x 480
Frame Rate	30 fps

Electrical and Operating Requirements	
Operating Ambient Temperature	-40°F (°C) to 140°F (60°C)
Maximum Wind Load	50 mph (~80.5 km/h)
Relative Humidity	5% to 95% non condensing
Line Voltage	100 - 240 VAC ~ 1.5A(MAX.)

Memory Storage	
Miovision Ultra SD Card	Proprietary, industrial-rated memory card designed for use with Scout.
Ultra SD Expected Life	Two (2) Years; approximately 50,000 write/erase cycles
Ultra SD Temperature Range	-40°C to +85°C
Memory Type	Industrial rated; Ultra MLC (proprietary)
Control Unit Memory Storage	Each slot supports up to a 32GB SD/SDHC card (7 days of video)

Camera	
Range	Super Wide Dynamic 120° horizontal view (Wide Lux chip embedded)
Television Lines	600TVL(Day); 650TVL(Night)
Noise Reduction	2D/3DNR
Stabilization	Digital Image Stabilizer

Warranty

1. One (1) Year Limited Warranty from date of delivery, the Hardware shall be free from defects in materials and workmanship, and function substantially in accordance with applicable documentation. At the date of purchase of the Hardware, the Customer may purchase an extended warranty for an additional 365 days.
2. The battery provided with the Scout Hardware is not included in or covered by any warranty of Miovision.
3. If Miovision replaces any piece of Hardware during the term of a warranty period, the warranty on such replacement piece of Hardware shall expire at the end of the applicable warranty period for the original piece of Hardware. Miovision may use refurbished portions of Hardware in replacement, provided such parts are of equal value

Miovision offers free support on the Scout Hardware during the life of the product. For more information, visit **help.miovision.com.** Email: **support@miovision.com** North American Toll-free: **1-855-360-7752**

B Specifications for the DJI Phantom 4 Pro

Appendix

Specifications

Aircraft	
Weight (Battery & Propellers Included)	1388 g
Diagonal Size (Excluding Propellers)	350 mm
Max Ascent Speed	Sport mode: 19.7ft/s(6 m/s); GPS mode: 16.4ft/s(5 m/s)
Max Descent Speed	Sport mode: 13.1ft/s(4 m/s); GPS mode: 9.8ft/s (3 m/s)
Max Speed	45 mph (72 kph) (S-mode); 36mph (58 kph) (A-mode); 31 mph (50 kph) (P-mode)
Max Tilt Angle	42° (Sport mode); 35° (Attitude mode); 25° (GPS mode)
Max Angular Speed	250°/s (Sport mode); 150°/s (Attitude mode)
Max Service Ceiling Above Sea Level	19685 ft (6000 m)
Max Flight Time	Approx. 30 minutes
Operating Temperature Range	32° to 104° F (0° to 40° C)
Satellite Systems	GPS/GLONASS
GPS Hover Accuracy Range	Vertical: ±0.1 m (With Vision Positioning); ±0.5 m (With GPS Positioning) Horizontal: ±0.3 m (With Vision Positioning); ±1.5 m (With GPS Positioning)
Gimbal	
Stabilization	3-axis (pitch, roll, yaw)
Controllable Range	Pitch: - 90° to + 30°
Max Controllable Angular Speed	Pitch: 90°/s
Angular Control Accuracy	±0.01°
Vision System	
Velocity Range	≤31 mph (50 kph) at 6.6 ft (2 m) above ground
Altitude Range	0 - 33 feet (0 - 10 m)
Operating Range	0 - 33 feet (0 - 10 m)
Obstacle Sensory Range	2 - 98 ft (0.7 - 30 m)
FOV	60°(Horizontal), ±27°(Vertical)
Measuring Frequency	10 Hz
Operating Environment	Surface with clear pattern and adequate lighting (lux > 15)
Infrared Sensing System	
Obstacle Sensory Range	0.6 - 23 ft (0.2 - 7 m)
FOV	70°(Horizontal), ±10°(Vertical)
Measuring Frequency	10 Hz
Operating Environment	Surface with diffuse reflection material, and reflectivity > 8% (such as wall, trees, humans, etc.)

Appendix

Camera	
Sensor	1'' CMOS; Effective pixels: 20 M
Lens	FOV (Field of View) 84°, 8.8 mm (35 mm format equivalent: 24 mm), f/2.8 - f/11, auto focus at 1 m - ∞
ISO Range	Video: 100 – 3200 (Auto); 100 - 6400 (Manual) Photo:100 - 3200 (Auto);100 - 12800(Manual)
Mechanical Shutter	8 - 1/2000 s
Electronic Shutter	1/2000 - 1/8000 s
Image Size	3:2 Aspect Ratio: 5472×3648 4:3 Aspect Ratio: 4864×3648 16:9 Aspect Ratio: 5472×3078
PIV Image Size	4096×2160 (4096×2160 24/25/30/48/50p) 3840×2160 (3840×2160 24/25/30/48/50/60p) 2720×1530 (2720×1530 24/25/30/48/50/60p) 1920×1080 (1920×1080 24/25/30/48/50/60/120p) 1280×720 (1280×720 24/25/30/48/50/60/120p)
Still Photography Modes	Single shot Burst shooting: 3/5/7/10/14 frames Auto Exposure Bracketing (AEB): 3/5 Bracketed frames at 0.7EV Bias Interval: 2/3/5/7/10/15/30/60 s
Video Recording Modes	H.265 • C4K: 4096×2160 24/25/30p @100Mbps • 4K: 3840×2160 24/25/30p @100Mbps • 2.7K: 2720×1530 24/25/30p @65Mbps 2720×1530 48/50/60p @80Mbps • FHD: 1920×1080 24/25/30p @50Mbps 1920×1080 48/50/60p @65Mbps 1920×1080 120p @100Mbps • HD: 1280×720 24/25/30p @25Mbps 1280×720 48/50/60p @35Mbps 1280×720 120p @60Mbps H.264 • C4K: 4096×2160 24/25/30/48/50/60p @100Mbps • 4K: 3840×2160 24/25/30/48/50/60p @100Mbps • 2.7K: 2720×1530 24/25/30p @80Mbps 2720×1530 48/50/60p @100Mbps • FHD: 1920×1080 24/25/30p @60Mbps 1920×1080 48/50/60p @80Mbps 1920×1080 120p @100Mbps • HD: 1280×720 24/25/30p @30Mbps 1280×720 48/50/60p @45Mbps 1280×720 120p @80Mbps
Max. Bitrate Of Video	100 Mbps
Supported File Systems	FAT32 (≤ 32 GB); exFAT (> 32 GB)
Photo	JPEG, DNG (RAW), JPEG + DNG
Video	MP4/MOV (AVC/H.264; HEVC/H.265)
Supported SD Cards	Micro SD, Max Capacity: 128GB. Write speed ≥15MB/s, class 10 or UHS-1 rating required
Operating Temperature Range	32° to 104° F (0° to 40° C)

Remote Controller	
Operating Frequency	2.400 - 2.483 GHz and 5.725 - 5.825 GHz
Max Transmission Distance	2.400 - 2.483 GHz (Unobstructed, free of interference) FCC: 4.3 mi (7 km); CE: 2.2 mi (3.5 km); SRRC: 2.5 mi (4 km) 5.725 - 5.825 GHz (Unobstructed, free of interference) FCC: 4.3 mi (7 km); CE: 1.2 mi (2 km); SRRC: 2.5 mi (4 km)
Operating Temperature	32° to 104° F (0° to 40° C)
Battery	6000 mAh LiPo 2S
Transmitter Power (EIRP)	2.400 - 2.483 GHz FCC: 26 dBm; CE: 17 dBm; SRRC: 20 dBm 5.725 - 5.825 GHz FCC: 28 dBm; CE: 14 dBm; SRRC: 20 dBm
Operating Voltage	1.2 A @7.4 V
Video Output Port	GL300E: HDMI, USB GL300F: USB
Mobile Device Holder	GL300E: Built-in Display device (5.5 inch screen, 1920×1080, 1000 cd/m^2, Android system, 4G RAM+16G ROM) GL300F: Tablets and smartphones
Charger	
Voltage	17.4 V
Rated Power	100 W
Intelligent Flight Battery (PH4-5870mAh-15.2V)	
Capacity	5870 mAh
Voltage	15.2 V
Battery Type	LiPo 4S
Energy	89.2 Wh
Net Weight	468 g
Operating Temperature	14° to 104° F (-10° to 40° C)
Max. Charging Power	100 W

Appendix

Upgrading the Firmware

Use DJI Assistant 2 or the DJI GO 4 app to upgrade aircraft and Remote Controller.

Upgrading the Aircraft Firmware

Method 1: Using the DJI Assistant 2

1. Power on the aircraft and connect it to a computer with a USB cable.
2. Launch DJI Assistant 2 and login with a DJI account.
3. Select “Phantom 4 Pro/Pro+” and click “Firmware Upgrade” on the left.
4. Select the firmware version required.
5. DJI Assistant 2 will download and upgrade the firmware automatically.
6. Restart the aircraft after the firmware upgrade is complete.

Method 2: Using the DJI GO 4 App

1. Ensure the both the aircraft and the remote controller are powered on and connected.
2. For Phantom 4 Pro, connect the Micro USB port of the aircraft to the mobile device with the USB OTG cable.

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